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Cryogenic time-domain multiplexer based on SQUID arrays and superconducting/normal conducting switches

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Abstract. We have demonstrated the operation of a 12-channel Beyer-style SQUID-based time domain multiplexer. It was manufactured using a fabrication process that is cross-compatible between VTT and IPHT-Jena. The multiplexer consists of twelve 12-SQUID series arrays, each shunted by a Zappe-style interferometer array acting as a flux-controlled superconducting/normal conducting switch. By keeping all switches but one in the superconducting state, it is possible to select one active readout channel at a time. A flux feedback coil common to all SQUID arrays allows realization of a flux-locked loop. We present characteristics of the multiplexer and measurement data from experiments with a 25-pixel X-ray calorimeter array operated at $T < 100$ mK in a dilution refrigerator.

1. Introduction

Transition-edge sensors (TES) designed for mK temperatures offer state of the art energy resolution in single-photon spectroscopy applications from soft X-rays to γ -rays. Under voltage bias condition, the TES operates with strong negative electro-thermal feedback, converting the energy of an absorbed incident photon to a decrease in Joule heating measured as an output current pulse.

Multiplexing is the only practical way to read out large arrays of TES pixels. TES calorimeter multiplexing has been demonstrated in the time [1], frequency [2] and code [3] domains (*TDM*, *FDM* and *CDM*). TDM is so far the most common and mature approach, however it suffers from a noise penalty [4] which limits the number of channels that could be multiplexed without degradation in energy resolution. FDM and CDM do not have the noise penalty but are more difficult to implement.

Thanks to their low noise, low power dissipation and versatility, SQUIDs have been widely used both as amplifying and modulating elements in the readout of TES detectors [1], [2], [3], [4]. The output signals of TES calorimeters optimized for X-rays are particularly difficult to multiplex due to their fast characteristic times, requiring a fast multiplexer and readout channel with high Shannon information capacity.



2. SQUID multiplexer

The SQUID multiplexer chip was designed at VTT and fabricated at IPHT-Jena using a process that is cross-compatible between the two institutes. It consists of 12 SQUID arrays each having 12 individual SQUID cells connected in series. The arrays have separate input coils with mutual inductance $M^{-1} = 10 \mu\text{A} / \Phi_0$. In addition, there is a flux feedback coil common to all arrays. The chip has a compact 3×3 mm form factor.

In a topology resembling Beyer's [5], each array is shunted by a flux-controlled on-off normal conducting/superconducting switch. However, in our design we have used 48-series arrays of Zappe-style three-junction interferometers [6] to realize the switches. These devices were initially proposed as building blocks for fast digital logic; in our work we take advantage of their square-shaped flux-voltage response, which alleviates the effect of noise in the address lines.

3. Experimental setup

Experiments were carried out in a Bluefors BF-LD400 cryogen-free dilution refrigerator. A schematic diagram of the setup is shown on Figure 1.

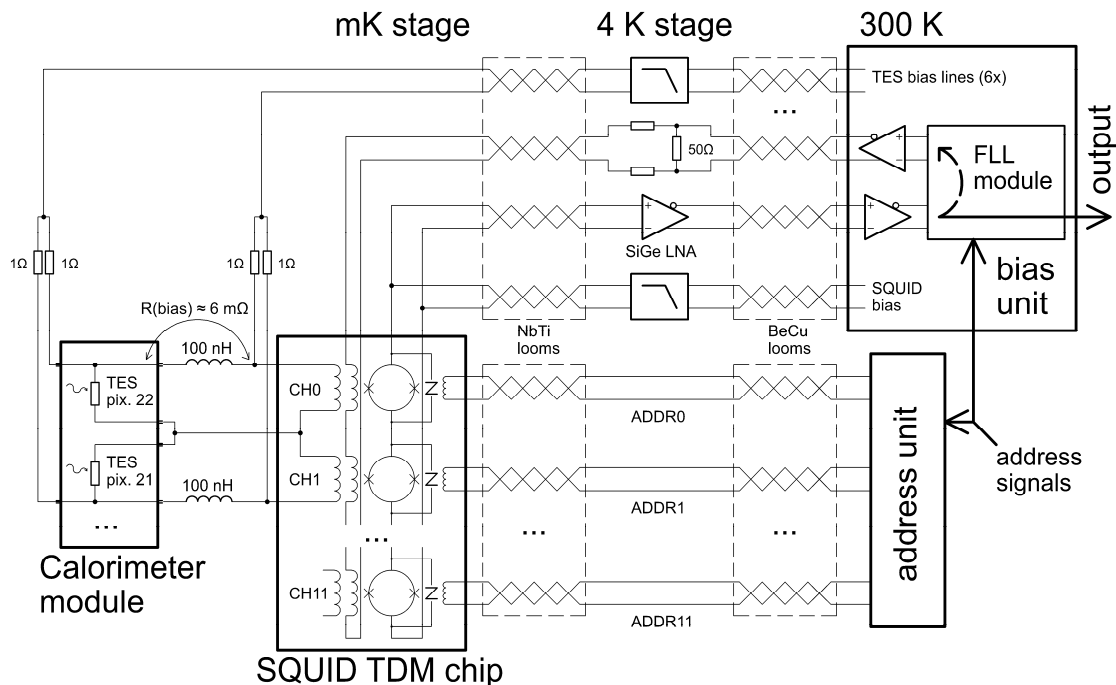
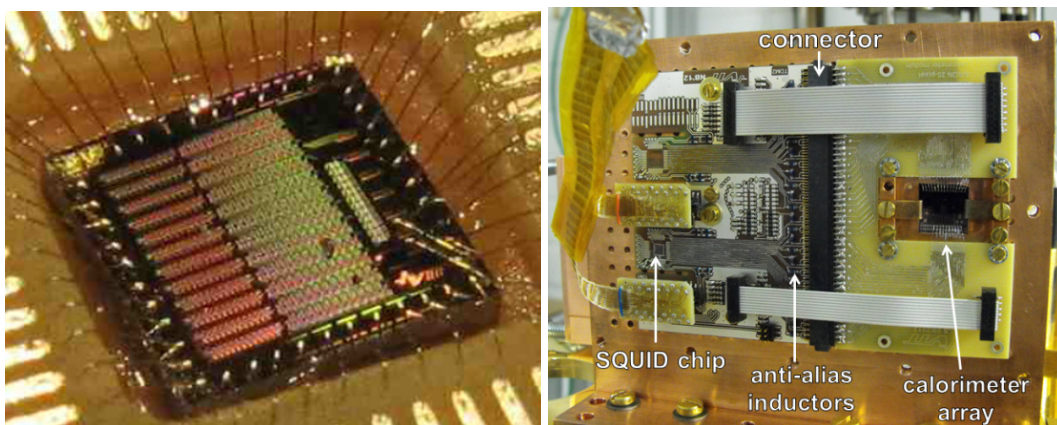


Figure 1. Schematic diagram of the experimental setup.



A.

B.

Figure 2. Photographs of the **A.** SQUID multiplexer chip **B.** mK stage experimental box.

3.1. mK stage

A copper box containing the calorimeter module, anti-alias filters, TES bias-splitting resistors and the SQUID multiplexer (Figure 2 A) was attached to the mixing chamber plate (Figure 2 B). The 25-pixel X-ray calorimeter module from SRON [7] was mounted on a circuit board equipped with a 1.27 mm pitch double-row connector. Commercial 100 nH SMD inductors were used as Nyquist filters and bias resistors simultaneously. The series connection of one such inductor and two mated connector contacts provided the bias resistance of 6 m Ω , while all PCB traces and bondwires in the TES-SQUID input loop were superconducting. A ^{55}Fe radioactive source was used to irradiate the sensor array through a hole drilled in the copper box lid.

3.2. 4 K stage

The electronics at the quasi-4 K plate were contained within a steel shielding box. Apart from various passive filters and attenuators, this box housed the cryogenic low-noise SiGe transistor amplifier [8] used to read out the SQUID multiplexer output voltage.

3.3. Room-temperature electronics

The room-temperature electronics system was divided into two functional blocks: bias unit and address unit. The bias unit contained drivers for various bias lines, as well as the differential receiver for the cold SiGe amplifier and the flux-locked loop (FLL) module. The address unit contained a 16-channel CMOS multiplexer which translated binary codes into boxcar current signals driving the address lines. Binary address signals were generated by a CPLD and fed simultaneously to the address unit and the FLL module. The output signals were digitized by a commercial 14-bit acquisition unit with Ethernet interface [9].

3.4. Analog multiplexed flux-locked loop

In order to accommodate full X-ray pulses within the SQUID dynamic range and linearize the response of the arrays, a FLL was implemented. Given the high signal bandwidth of the pulses and the multiplexing factor, one needs sufficiently fast loop dynamics. Typically, in TDM systems the FLL has been implemented digitally using FPGA logic with memory for each channel [10]. In the present work we have developed a different approach, which is fully analog.

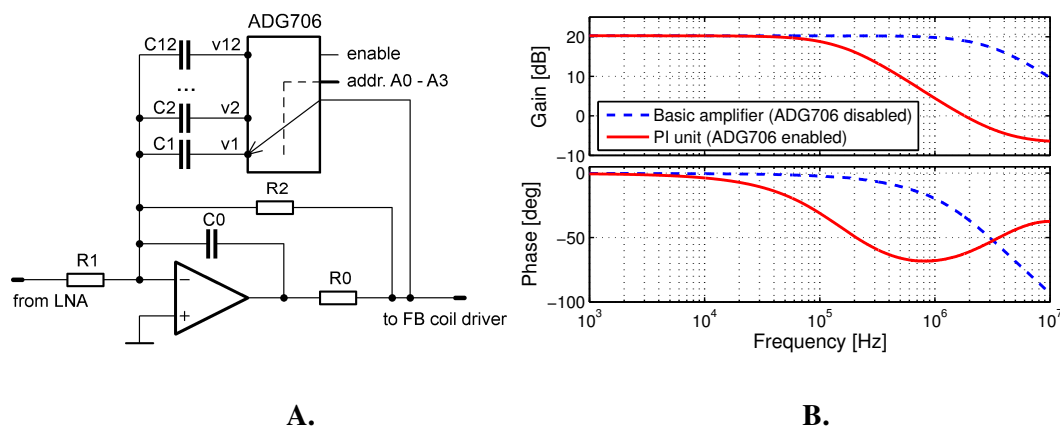


Figure 3. Multiplexed FLL unit: **A.** circuit diagram **B.** gain and phase vs frequency.

The circuit shown on Figure 3 A. acts as a proportional-integral (PI) unit (Figure 3 B.) within the FLL. At low frequencies the gain is constant and is set by the ratio $R2/R1$. At high frequencies, the $C1 - C12$ capacitor bank implements the integrating function and analog memory. The left-hand side terminals of the capacitors are all kept at the 0 V virtual ground, while the right-hand side is either within the feedback path (channel on) or effectively floating (channel off). This configuration resembles a multi-channel track-and-hold circuit. A fast operational amplifier is used to guarantee rapid switching between channels.

4. Results

Figure 5 A shows a typical X-ray pulse obtained in quasi-static (non-multiplexed) mode. The pulse has a very fast rising edge (Figure 5 B) due to the faster-than-optimal anti-alias filters. An energy resolution of ≈ 20 eV was measured at 5.9 keV. The raw output sampled at 2 MHz is shown on Figure 5 C. From the pixel dwell time of 2 μ s, 4 samples (1 μ s) on the transient were discarded and the remaining 4 within the settled period were averaged to produce one sample in the demultiplexed signal (decimation factor of 8). Figure 5 D shows demultiplexed X-ray pulses from 8 channels. Pulse acquisition was triggered from 6 of the channels, while events from the other two were captured randomly. All events are clearly resolved into the respective channels and no cross-talk is evident.

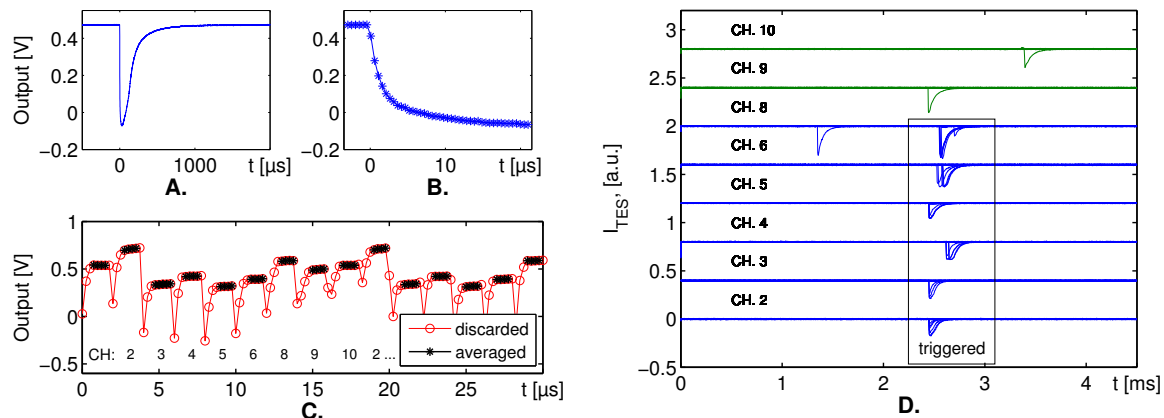


Figure 5. A. Typical X-ray pulse B. zoom-in of the falling edge of the pulse from A. C. raw multiplexed output D. demultiplexed pulses from 8 channels.

5. Conclusion

We have designed and fabricated a compact 12-channel SQUID multiplexer that is useful for quasi-static measurements and characterization. Dynamic operation in TDM is possible, but with added noise. The practical use of the component was demonstrated by multiplexing the signals of 8 TES X-ray calorimeters. Unlike more standard setups [4] that have two- or three-SQUID amplifier cascades, our system uses one SQUID stage and a cryogenic SiGe amplifier. An analog multiplexed FLL was successfully implemented and performed in a stable manner, despite the fast pulse rising edges. The ultimate energy resolution capability of the sensor array was not reached and we are working on improving the EMI and thermal performance of our experimental setup. As a parallel development, we are considering the use of three-junction Zappe interferometers as flux-controlled inductances for current-steering CDM [11].

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